A Discussion of Two Challenges of Non-Cooperative Satellite Refueling

51st AIAA/SAE/AIEE Joint Propulsion Conference
Orlando, July 27-29, 2015

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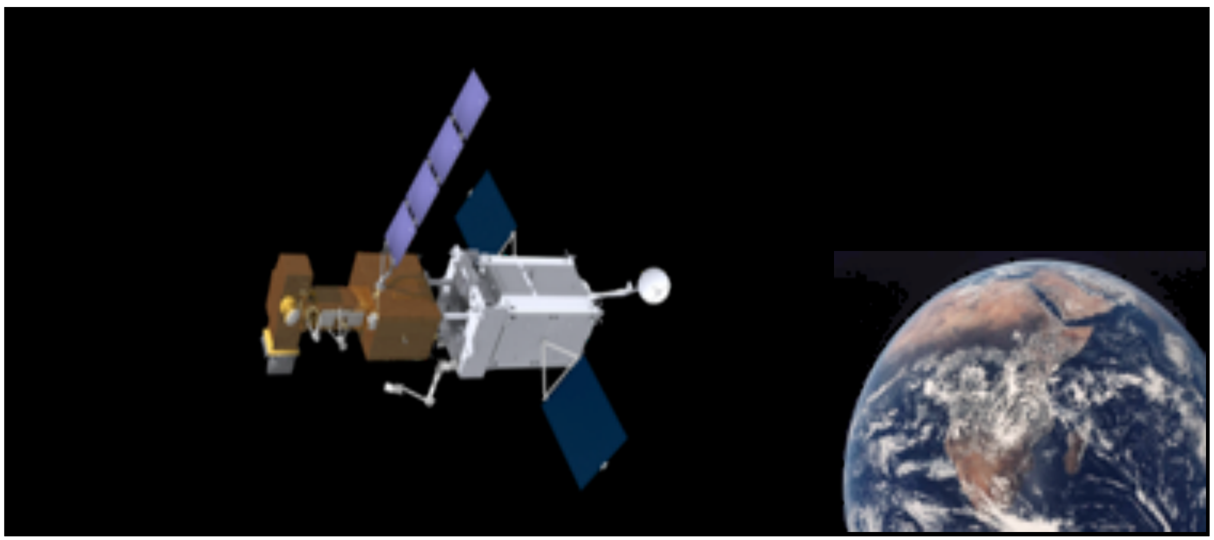
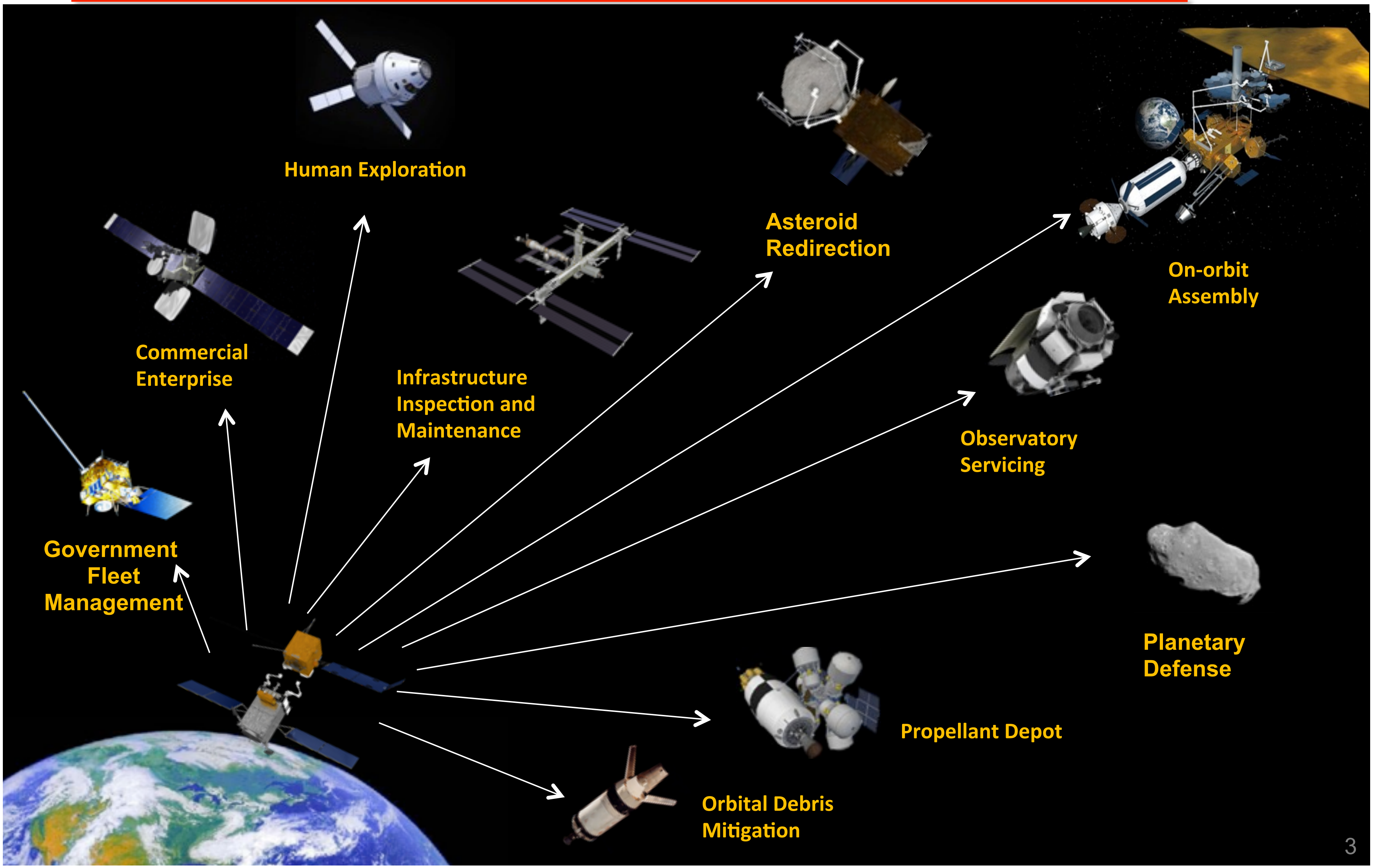
Satellite Servicing Capabilities Office
(In-Space Robotic Servicing)

- The Satellite Servicing Capabilities Office is responsible for the overall management, coordination, and implementation of satellite servicing technologies and capabilities for NASA.
  - Conducts studies
  - Conducts demonstration experiments in orbit and on the ground
  - Manages technology development and satellite servicing missions
  - Advises and designs cooperative servicing elements and subsystems

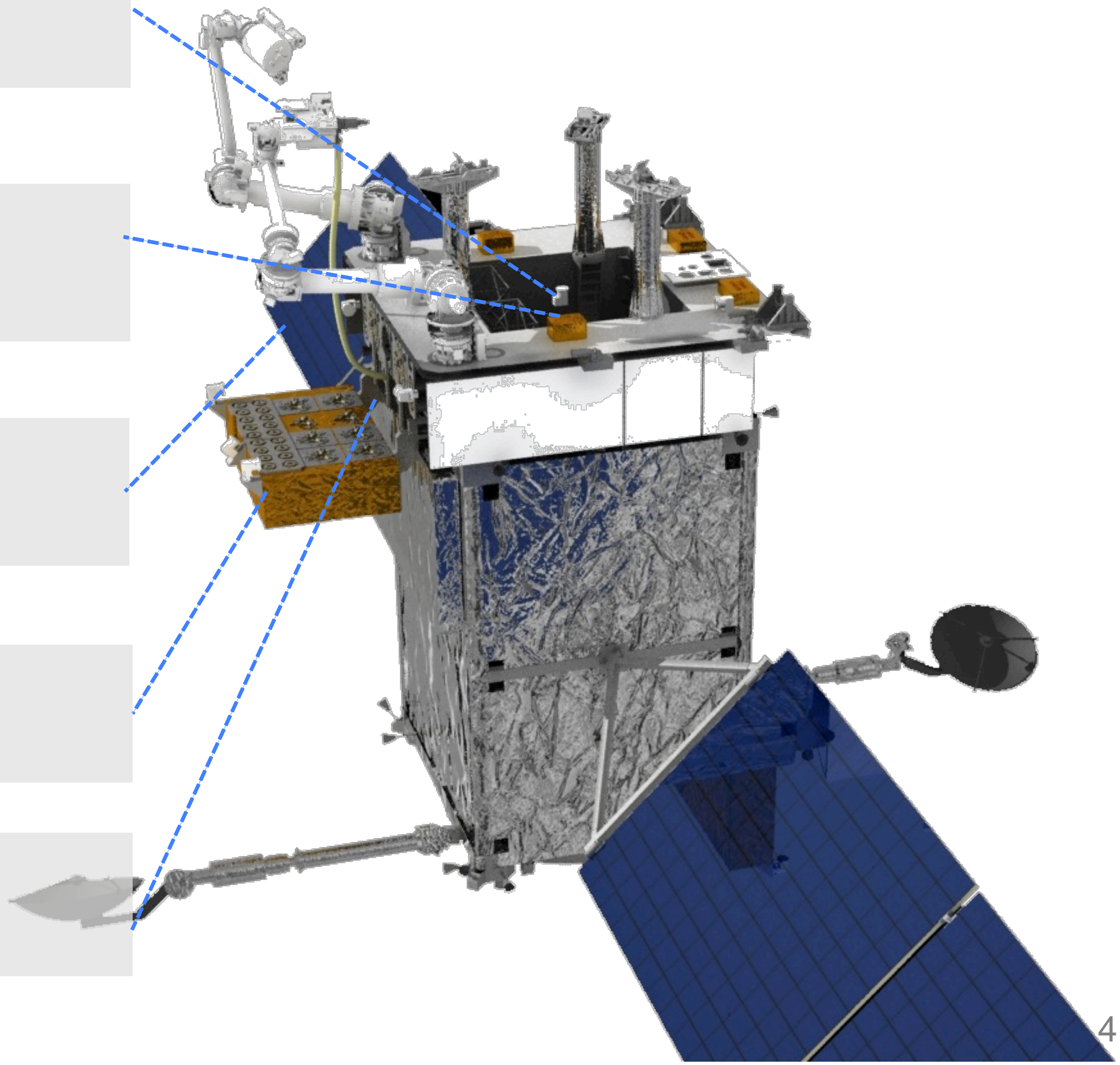


Servicing Extensibility



Critical Technologies

- Rendezvous & Prox Ops System
- High-speed, Fault-Tolerant Computing
- Dexterous Robotics
- Robotic Tools and Tool Drive
- Fluid Transfer



Fluid Transfer

Technology Maturation and Test Campaign

2005-2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

Oxidizer pump evaluation

Ethanol refueling on orbit

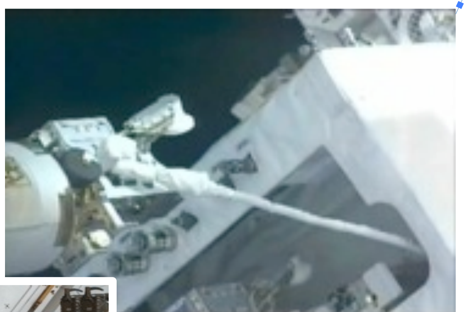
Hose tests in zero-g, NBL

CFC-113 & N2O4 transfer

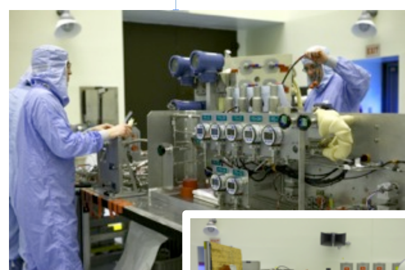
Comprehensive Refueling Tasks

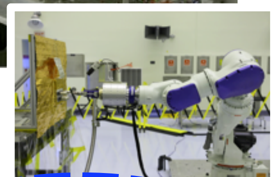
Propellant transfer system

Cryo and xenon transfer (RRM-3)

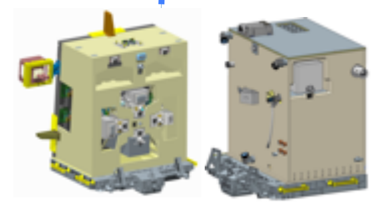


Robotic Refueling Mission demo of tools and procedures and transfer of ethanol



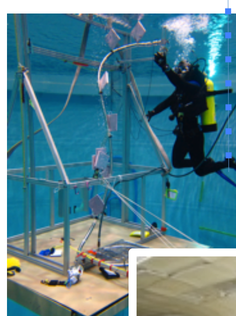


CFC-113 & N2O4 transfer at flight pressures, flow rates and quantities

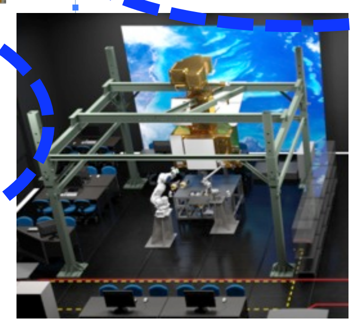


Demo of xenon recharge & cryogen transfer

Non propulsive vent test with hypergolic propellants

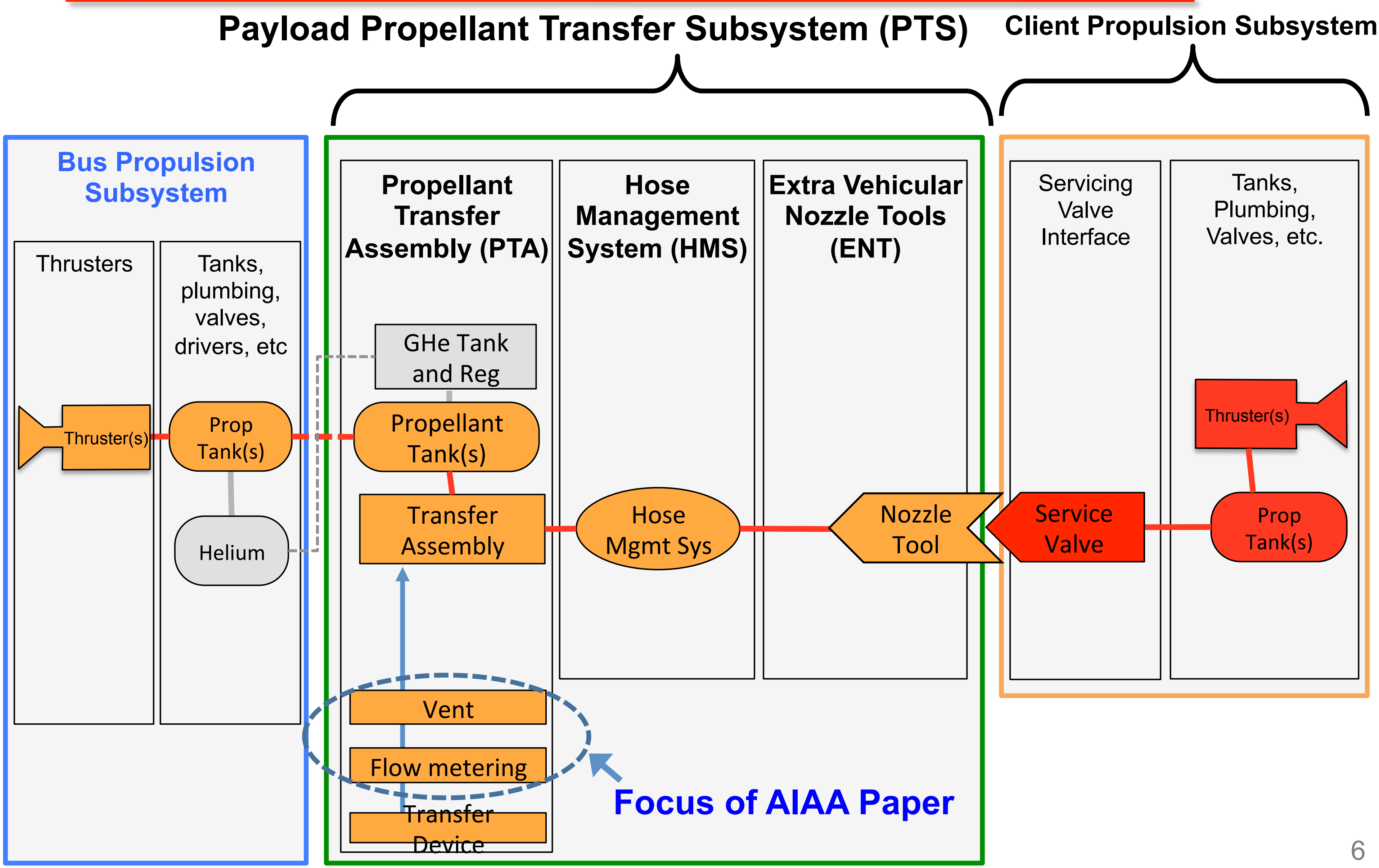


Neutral buoyancy and zero-g evaluations of flexible hose characteristics



Propellant Transfer System integrated into system-level test of refueling

Propulsion and Propellant Transfer Subsystems



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The Challenge of On Orbit Fluid Venting

Max Kandula, SGT, Inc.

Satellite Servicing Capabilities Office
http://ssco.gsfc.nasa.gov

The Challenge of On Orbit Fluid Venting

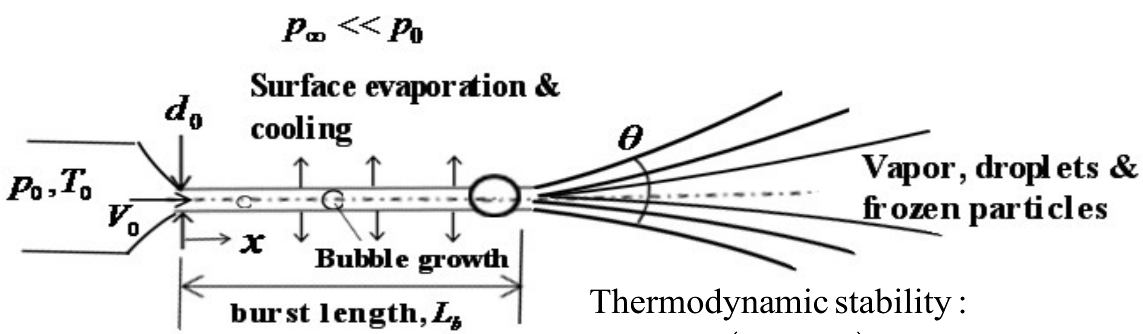
- There exists risk of fluid freezing near nozzle exit when fluids are vented into space
  - The liquid jets flash upon depressurization following venting
  - Bubble formation and growth lead to jet disintegration
  - Liquid droplets are formed, frozen and dispersed
  - There is likely plugging of the nozzle flow & surface contamination
  - Mission safety is at risk

- Understanding the basic physics of flashing jets affords the following benefits
  - Design optimum nozzle configurations
  - Estimate optimum jet parameters (pressure, temperature, velocity)
  - Evaluate nozzle heating requirements to eliminate freezing
  - Mission safety is thereby assured

Objectives

- Characterize flashing liquid jets
- Develop an analytical model for bubble dynamics in jets
- Predict jet behavior
  - Jet bursting length
  - Cone angle of dispersion
  - Droplet size and velocity (not presently considered)
- Validate the analytical model with existing data
  - Bubble growth in an unbounded medium (uniformly superheated)
  - Flashing liquid jets (test data available for water only)
- Improve the model capable of correlation/ validation to hypergolic propellant vacuum venting tests

Physical Processes in a Flashing Jet

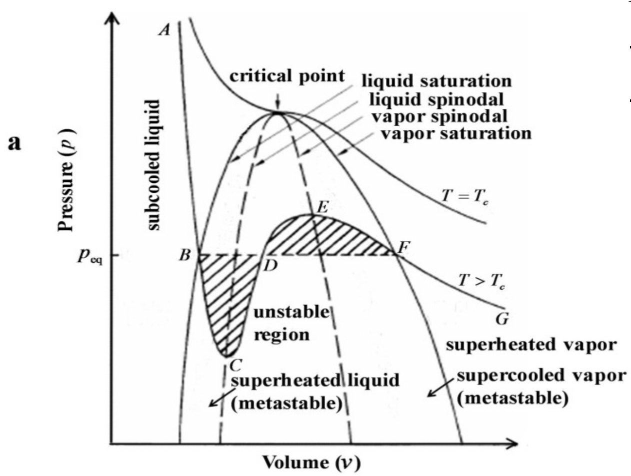


Thermodynamic stability :

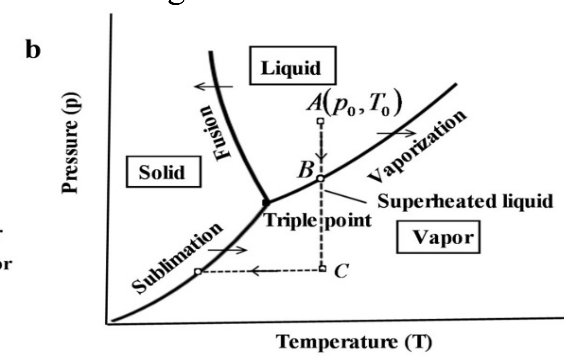
$R_c = 2\sigma / (p_v - p_\infty)$: Critcal bubble radius

– Bubbles collapse if the nucleation radius is less than R_c.

– Bubbles grow if the nucleation radius exceeds R_c.



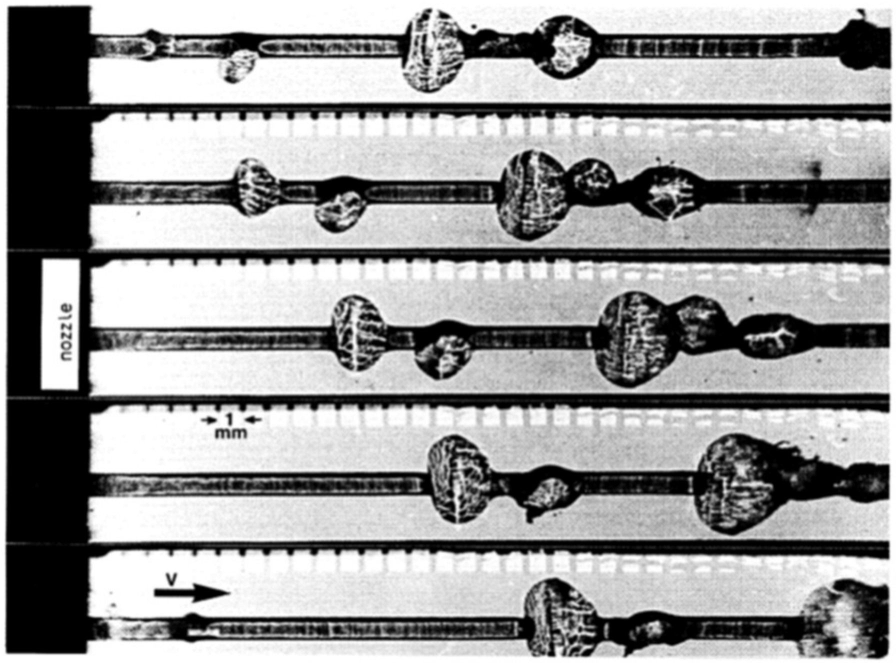
Pressure-Volume



Pressure-Temperature

- The physical processes in flashing jets are described by the pressure-volume and pressure-temperature diagrams.

Photographic Data of Wildgen and Straub (1989)



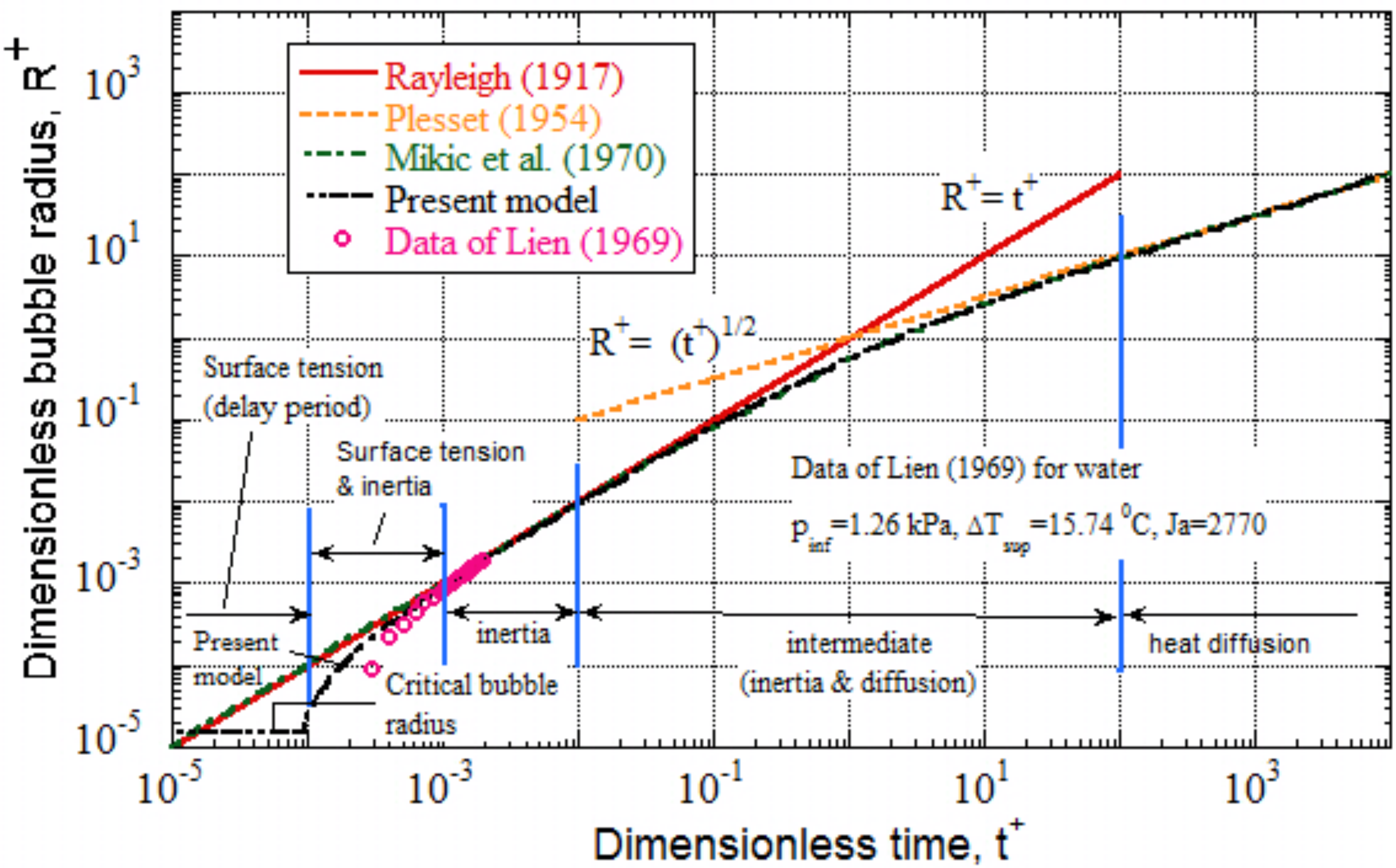
- *Evidence suggests that the bubble grows considerably larger relative to the jet size prior to disintegration (bursting).*

Present Model Development

- Bubble Growth in an Unbounded Medium
  - Extends MRG model (Mikic, Rohsenow & Griffith, 1970)
  - Accounts for surface tension (and delay period)
  - Accounts for initial bubble radius

- Bubble Growth in Flashing Liquid jets
  - Assumes bubble nucleation at the nozzle exit
  - Relates jet surface temperature to initial and triple point temperature
  - Accounts for surface tension at the jet surface (Muntz & Orme, 1987)
  - Postulates an improved jet burst criterion
    - Jet burst when bubble size exceeds 4 times the jet diameter
    - This criterion is guided by the photographic data (Wildgen & Straub, 1989)

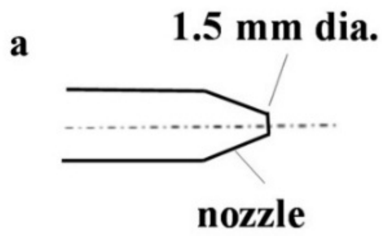
General Comparison & Validation with Existing Bubble Growth Models



- The present model is capable of characterizing the bubble growth in all phases including the surface tension controlled region.

Comparison for Flashing Jets Data of Fuchs & Legge (1979)

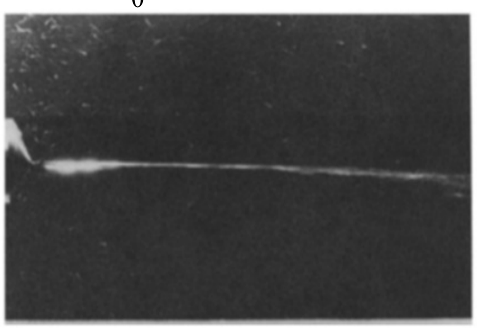
<u>Nozzle configuration</u>



<u>Jet structure</u>

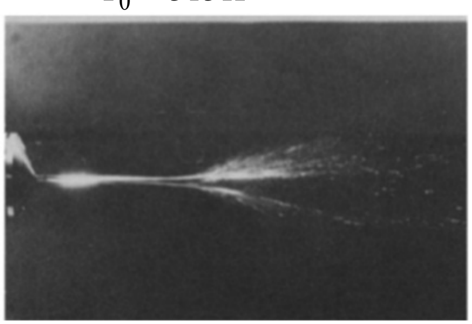
$T_0 = 293\,\mathrm{K}$

b

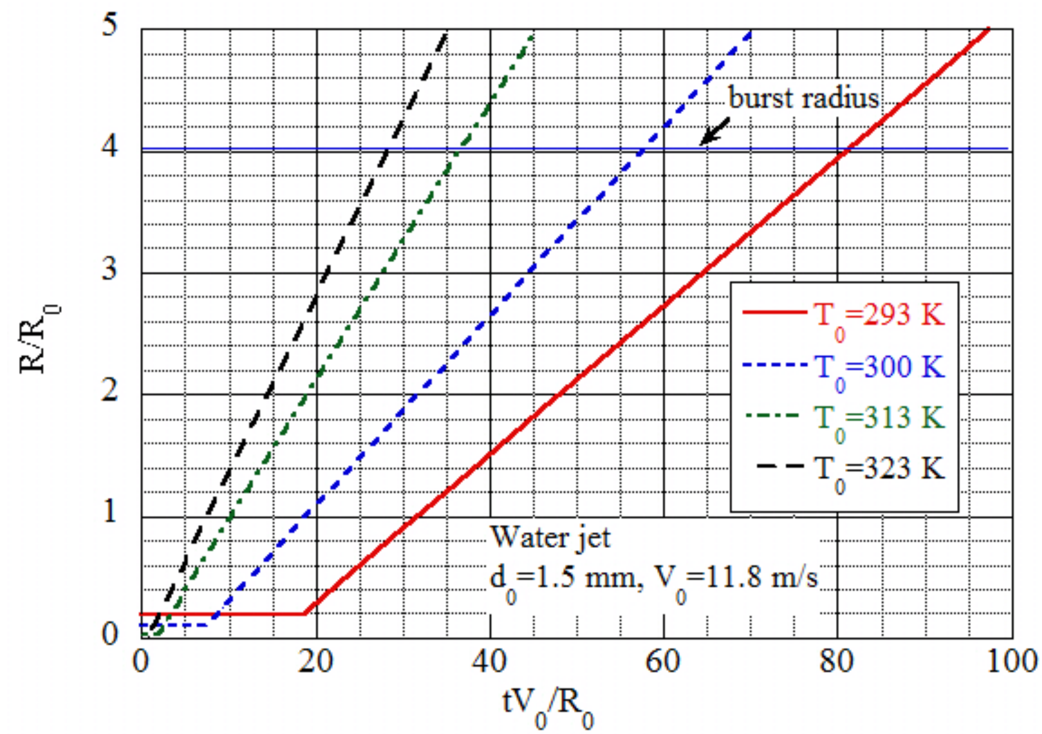


$T_0 = 313\,K$

c



<u>Predicted Bubble growth</u>

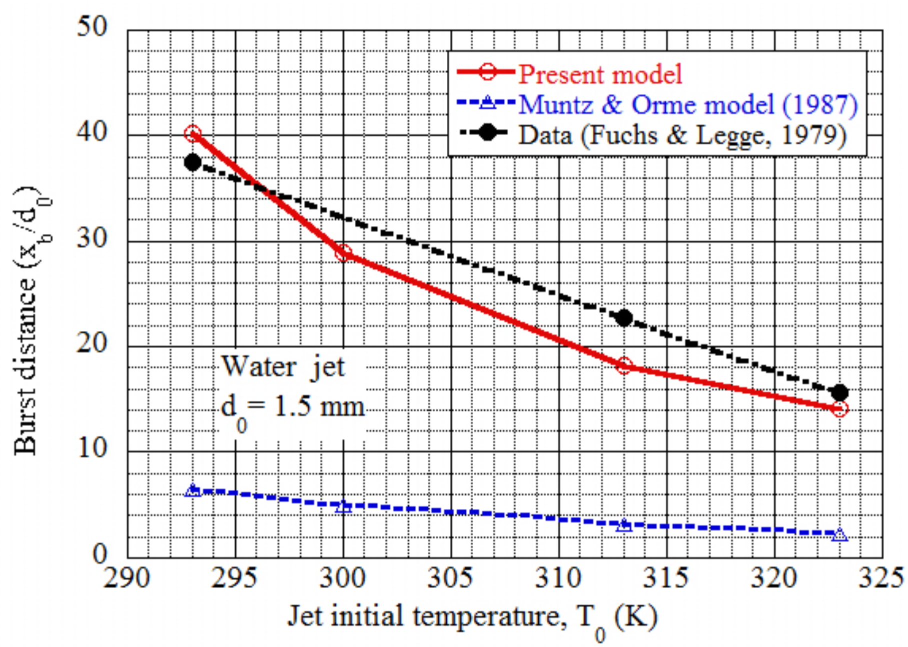


- The jet burst length decreases with an increasing inlet jet temperature.

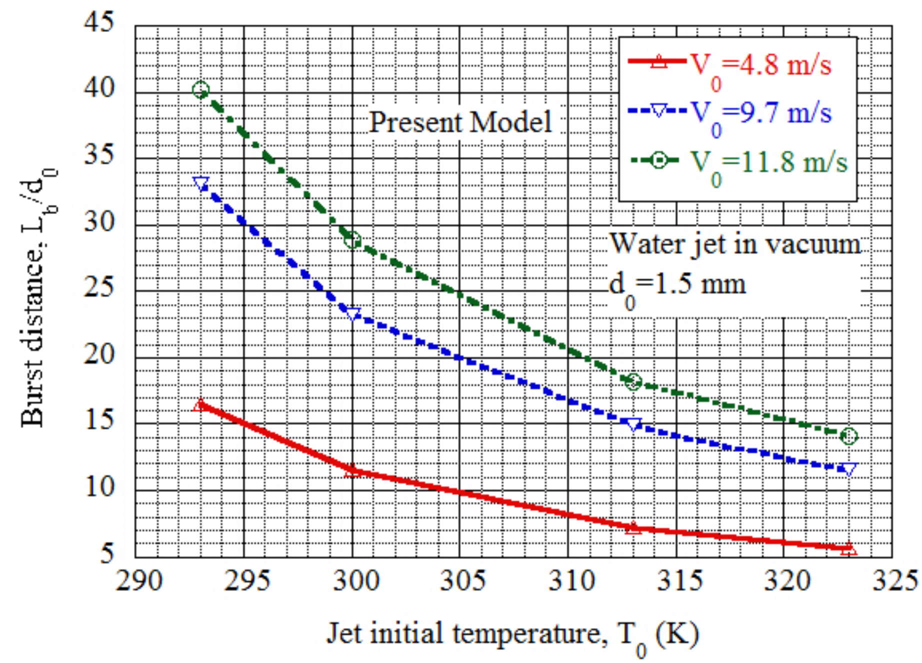
- The predicted bubble grows linearly with time.

Comparison for Flashing Jets
Data of Fuchs & Legge (1979): contd.

Jet Burst Distance



Effect of jet temperature

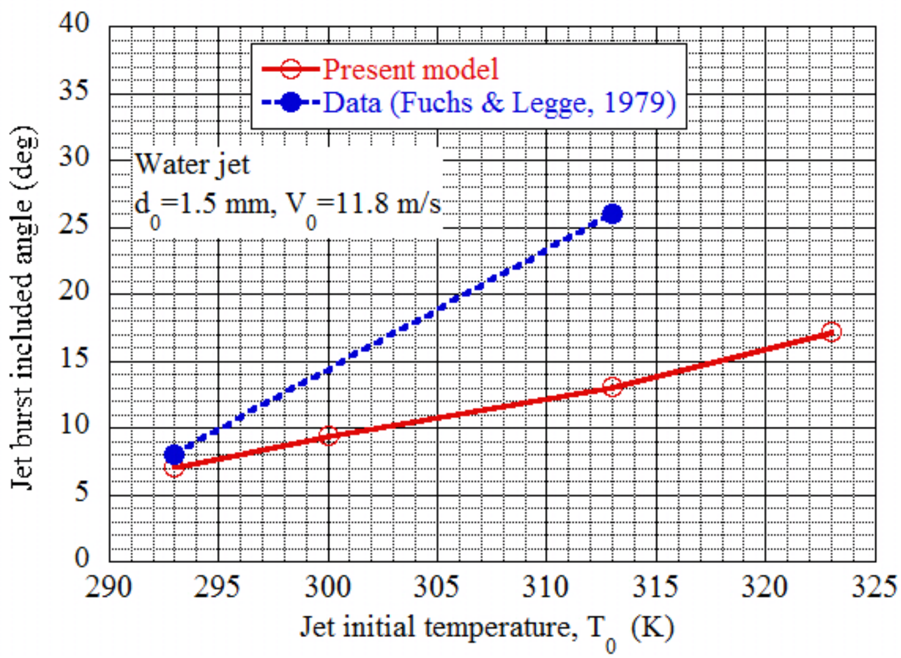


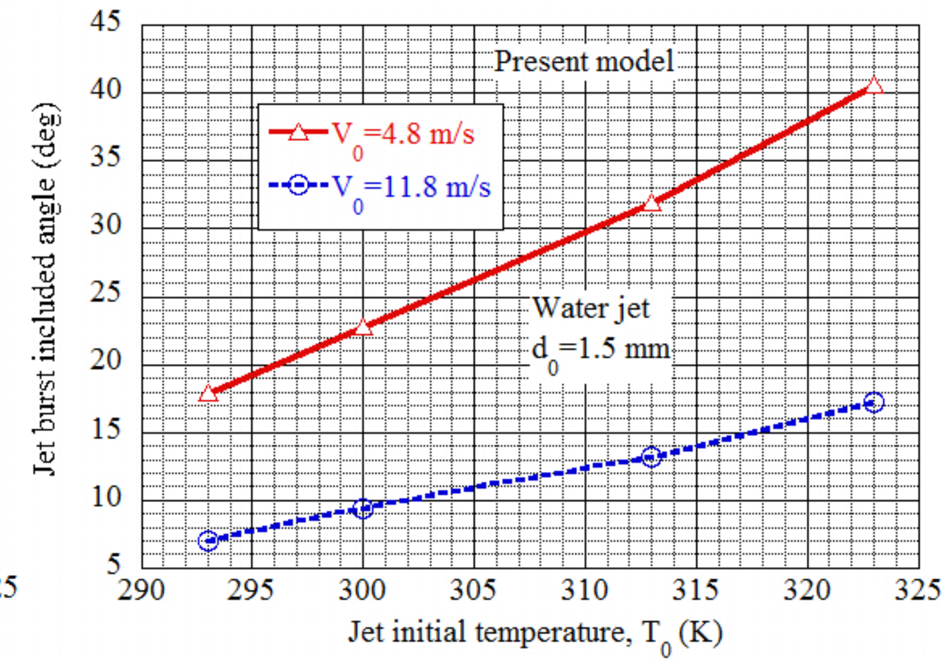
Effect of jet velocity

- *The burst length predictions of the present model compare well with test data for various jet temperatures. The burst length decreases with increasing jet temperature and increases with increasing jet velocity.*
- *The Muntz & Orme model predicts burst lengths an order of magnitude lower relative to the test data.*

Comparison for Flashing Jets Data of Fuchs & Legge (1979): contd.

Jet Cone Angle of Expansion (Burst Angle)





- *The jet burst included angle increases with increasing jet temperature, but decreases with increasing jet velocity.*
- *The model underpredicts the jet burst angle (perhaps due to vapor clouding: (jet boundary demarcation is difficult).*

Conclusions

- The proposed bubble growth model, accounting for surface tension and initial bubble radius was satisfactorily validated with existing water test data for unbounded medium as well as flashing jets.

- The model predicts that the jet burst distance increases with jet initial temperature, and decreases with a decrease in jet initial velocity, as demonstrated by past test data for water.

- The postulated burst criterion (jet bursts when the bubble size exceeds four times the jet diameter) has been validated in accordance with past test data for water.

- Continued validation with proposed testing for water and other fluids and nozzle configurations would strengthen the model
  - Test with water (serves as calibration of our test setup and instrumentation)
  - Test with hypergols and other fluids or mixed commodities
  - Investigate optimized Nozzle and orifice configurations for specific mission requirements

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The Challenge of On Orbit Propellant Mass Flow Measurement

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Satellite Servicing Capabilities Office
http://ssco.gsfc.nasa.gov

The Challenge of On Orbit Propellant Mass Flow Measurement

- There exists risk of over- or under-filling the client propulsion system while refueling on orbit
  - Under-filling client could result in premature loss of propulsion or mission loss in some cases
  - Over-filling could result in over pressurization or in the case with multiple clients reduced propellant transfer capability to additional clients

- Understanding and accurately measuring the mass of transferred propellant affords the following benefits
  - Optimization of tankage configs. (few tanks produced for many clients)
  - Optimize transfer parameters (pressure, temperature, & flow rate)
  - Verify total propellant load with defined accuracy
  - Increase mission safety and reduce alternative gauging risk
  - Real-time evaluation of tankage and system heating vs. flow rate
    - Many existing clients have limited instrumentation for health monitoring during refueling

Overview

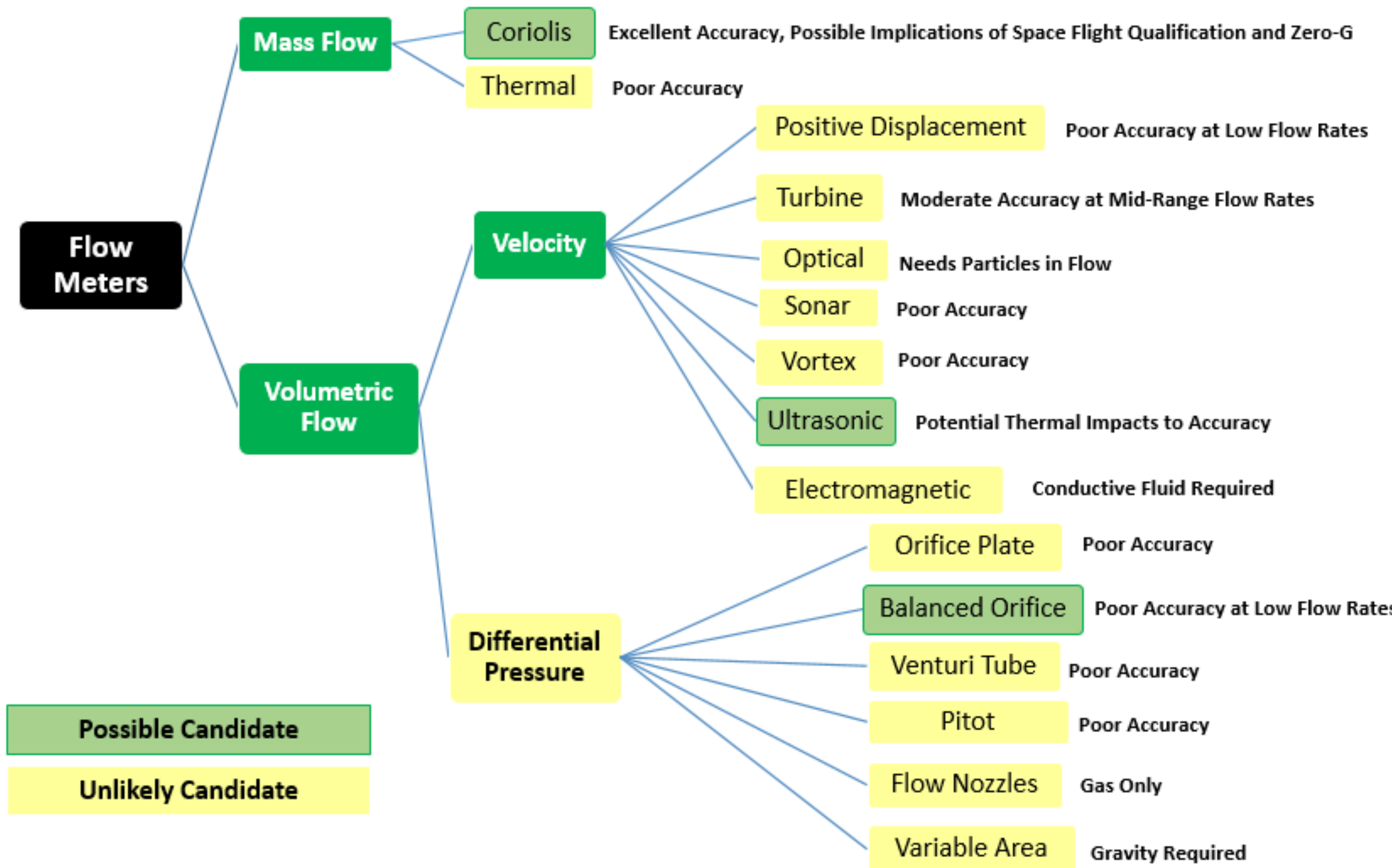
- PTS Flow Meter Goals
- Flow Meter Technology Trade Study
- Tested Flow Meters
- Test Setup and Operation
- Comparison of Flow Meter Performance
- Conclusion

PTS Flow Meter Goals

- A non-cooperative or cooperative multi-client satellite refueling system has the need for measuring commodity mass transferred to the client spacecraft with the following relevant component-level goals:
  - Accuracy: 0.5% accuracy (overall error)
  - Common design compatible and operable with: N_2O_4, MMH, and N_2H_4
  - Volumetric flow rates: 0 to about 6 liters per minute
  - Commodity temperatures: 10-50 deg C
  - Geosynchronous or low earth orbit operational environment
  - External load environments during launch and flight

Flow Meter Technology Trade Study

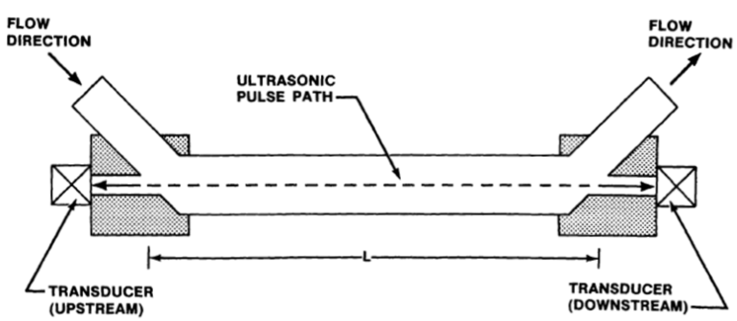
- Five different flow meters were tested during the PTA test campaign
  - One ultrasonic, three Coriolis, and one balanced orifice
  - Research from Baird and others shown at right (further information in backup and report)



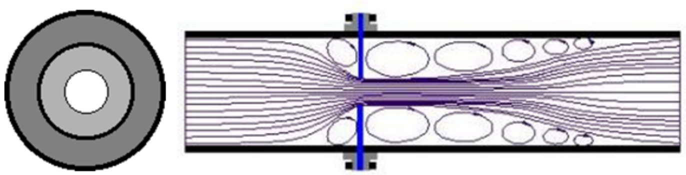
Tested Flow Meters

- In-line Ultrasonic (UFM)
  - Volumetric flow
  - Based on contra-propagating transit time flow measurement method
  - Flow rate determined by detected difference in time of travel in-line with flow
  - Transmitter pair - one upstream one downstream
  - No moving parts
  - Gas bubbles in flow disrupt sound signal which could lead to degraded accuracy
- Balanced Orifice (BFM)
  - Volumetric flow
  - Multi-hole orifice plate is balanced to minimize vortex flow
  - Flow rate is proportional to square root of differential pressure across the orifice plate (Bernoulli principle)
  - Requires highly accurate pressure sensors to measure accurate mass flow rates
  - Degraded accuracy at lower flow rates

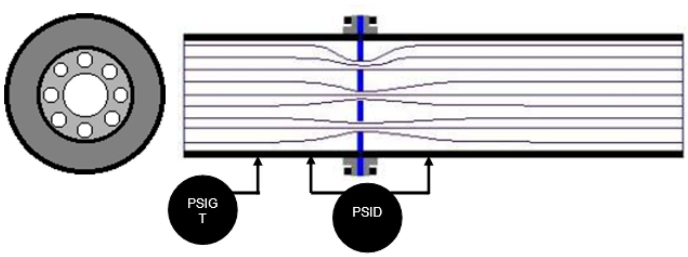
UFM



Single Hole Orifice

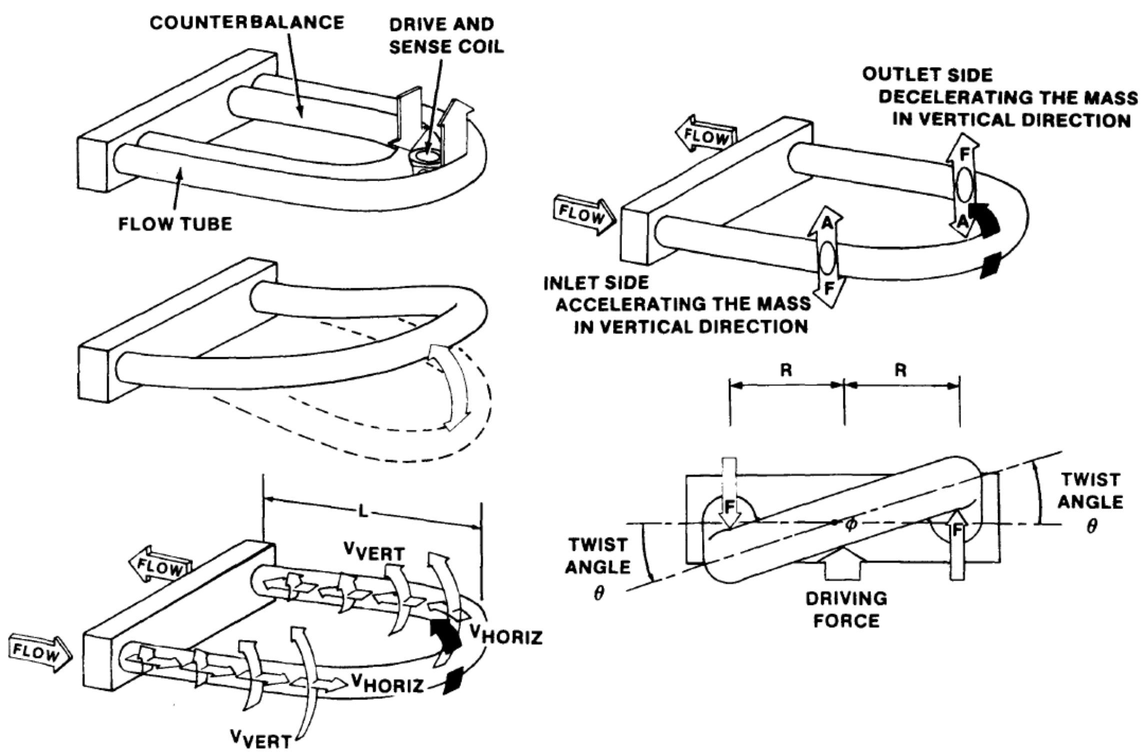


BFM



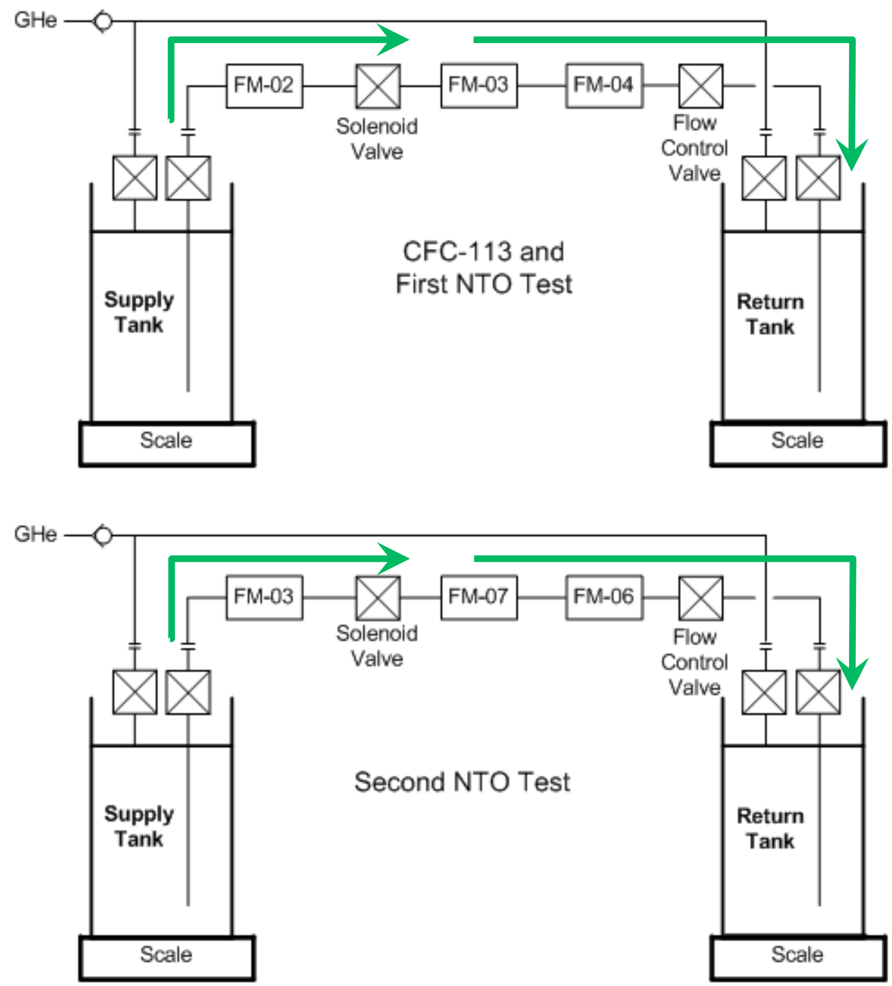
Tested Flow Meters (cont.)

- Coriolis
  - Mass flow
  - Flow passes fluid through U-shaped sensor tube
  - Induced natural frequency vibration perpendicular to flow direction
  - Coriolis effect introduced by moving mass causes tube to deform or twist proportional to mass flow rate
  - Can also measure fluid density and temp.
  - No moving parts in flow stream (active components required for vibration induction)



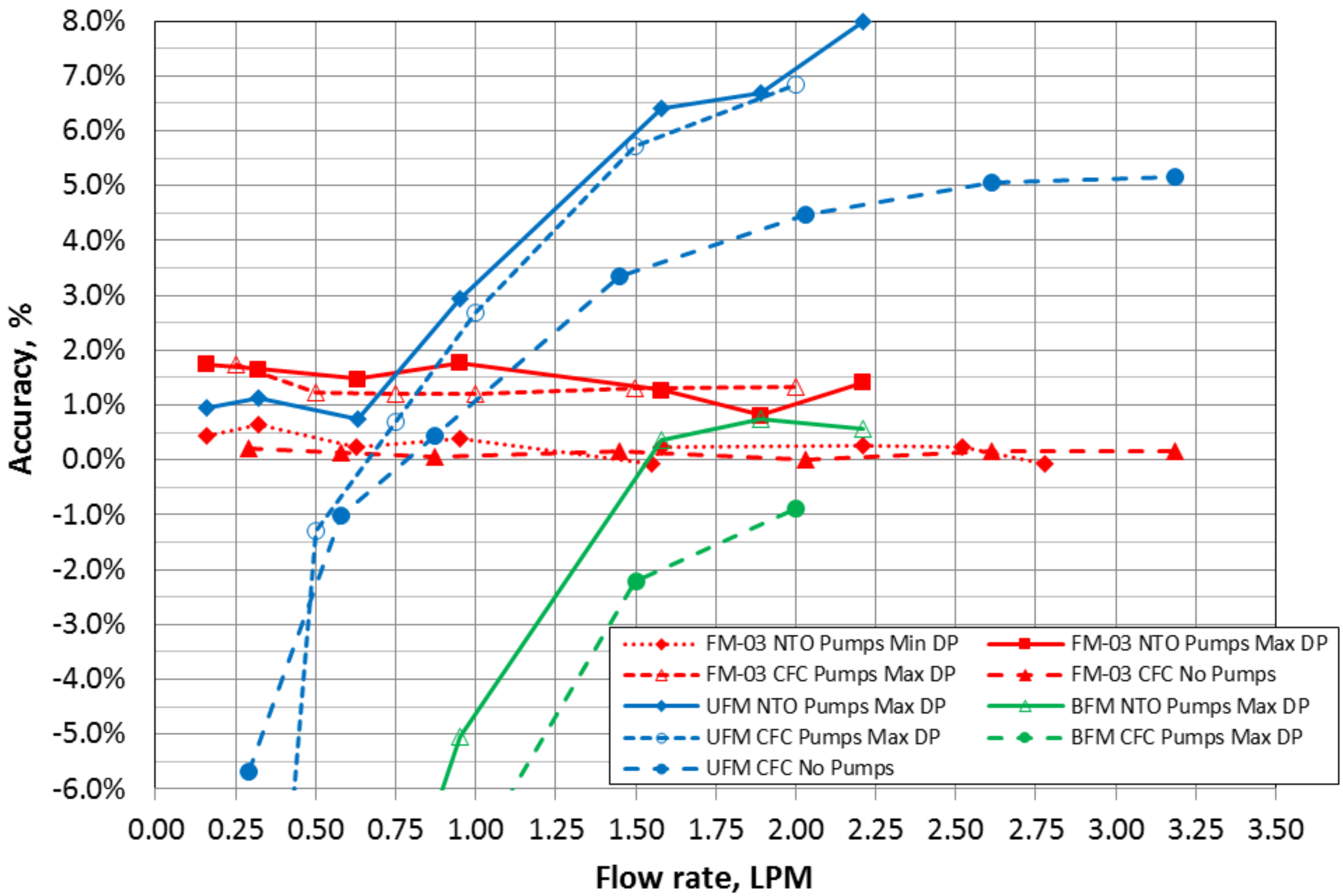
Test Setup and Operation

- Fluid transferred from supply tank passes through various flow meters then enters receiver tank
- Flow control valve positioned upstream of receiver tank
- Flow meters located up or downstream of solenoid valve that controlled initiation and termination
- Pressure was not regulated (tanks isolated from vent and pressure source during transfer)
- Precision scales used as standards
  - Accuracy of <0.1% verified before/after test
- Mass totalizer was integrated in control and data recorder
- Flow meter totalizers tabulated independently
- In-line heat exchanger
  - Downstream of supply tank, not shown
- Constant mass flow rate maintained by pumps or needle flow control valves
- Temps., pressure, valve states, scale readings, and flow rate telemetry recorded



Flow Meter Test Results

- Results from 29 separate runs for nominal 11 lb transfer runs at ambient fluid temperature



Comparison of Flow Meter Performance

- In-line Ultrasonic (UFM)
  - Strongly dependent on flow rate
  - Exhibited poor repeatability at flow rates less than about 1.3 LPM
  - Had issues with fluid temperature fluctuations and hot fluids
  - Unacceptable for application under consideration

- Coriolis
  - Highest accuracy of three technologies tested
  - No issues with temperature or fluid changes

- Balanced Orifice (BFM)
  - Accuracy sensitive to flow rate specifically at low flow rates (<1.5 LPM)
  - Sensitive to commodity type
  - Unacceptable for application under consideration

Comparison of Flow Meter Test Results for Stated Goals

	UFM	BFM	Coriolis
Accuracy of 0.5% or better	Failed	Failed	Passed
Same design compatible and operable with N_2O_4, MMH, and N_2H_4	Failed*	Passed*	Passed*
Able to measure volumetric flow rates from about 0 to 6 LPM	Passed	Passed	Passed
Able to operate at commodity temperatures of 10-50 deg. C	Failed	Passed	Passed
Able to withstand geosynchronous earth or low earth orbit operational environment	Unknown (but partially qualified)	Unknown	Unknown (future work)
Able to withstand external load environments during launch and flight	Unknown (but partially qualified)	Unknown	Unknown (future work)

*Only tested with N2O4; future work to verify with MMH and N2H4

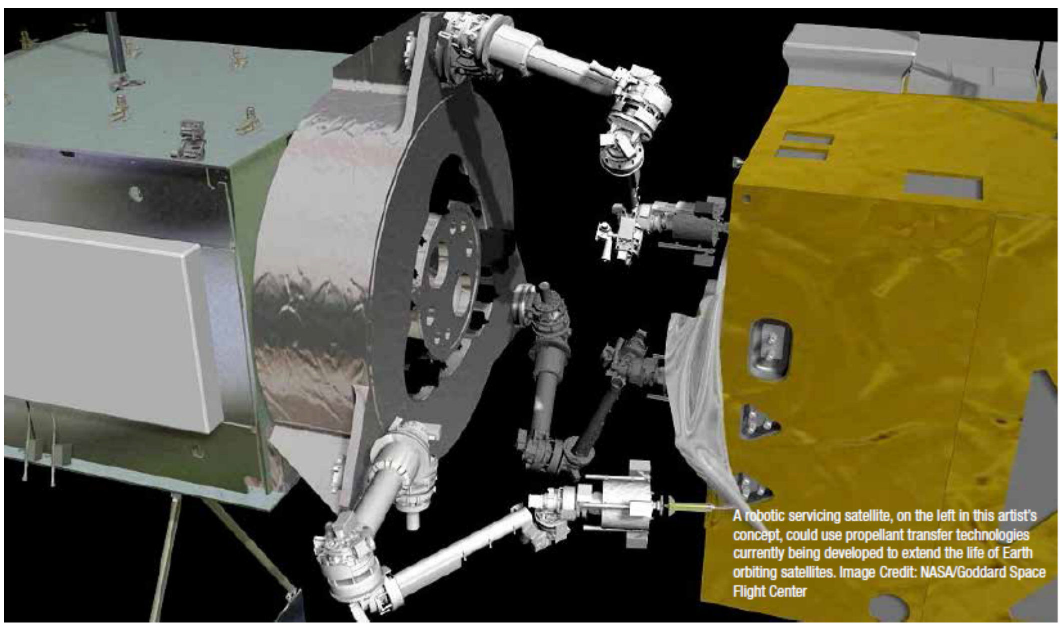
Conclusions

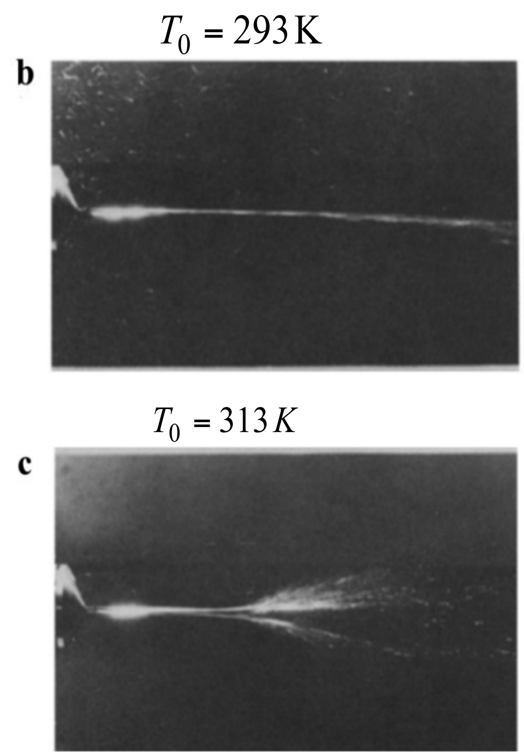
- Based on flow testing and report evaluation conducted to date, Coriolis flow meter technology outperforms the other technologies for the PTS
  - Also applicable for other on-orbit commodities

- Further testing and evaluation is required to make a final recommendation including
  - Environmental and external load testing
  - Validation in micro-gravity environment

Overall Conclusions

- Two major challenges have been addressed for on-orbit propellant transfer technologies
- Significant risks have been realized and reduced for propellant transfer system
- Continued testing is needed and will be taking place to further reduce risks





The Challenge of On Orbit Fluid Venting
Back-Up Slides

Bubble Growth Models for an Unbounded Medium

- Lord Rayleigh (1917)
  - Rayleigh equation
  - Inertia-controlled bubble growth (isothermal)
  - Neglects surface tension effect (delay period) and initial bubble size
  - Valid for early stage of bubble growth (small times)

- Plesset & Zwick (1952)
  - Rayleigh-Plesset equation (extended Rayleigh equation)
  - Heat diffusion controlled bubble growth (isobaric)
  - Valid for large times (asymptotic growth)

- Mikic, Rohsenow & Griffith (1970): **MRG** Model
  - Combines Rayleigh and Plesset & Zwick solutions
  - Valid for combined inertia- and heat diffusion-controlled region
  - Neglects surface tension and initial bubble radius

Models of Rayleigh & Plesset & Zwick

Rayleigh solution (1917) :

$$R = \left[\frac{2}{3} \frac{p_v - p_\infty}{\rho_f} \right]^{1/2} t : \text{ Inertia - controlled bubble growth (small time)}$$

Plesset & Zwick (1952) :

$$R = 2\left(\frac{3}{\pi} \alpha_f t \right)^{1/2} Ja : \text{Heat - conduction controlled (large time)}$$

where

$$Ja = \frac{\rho_f c_f \Delta T_{\text{sup}}}{\rho_v h_{fg}} : \text{Jacob number (sensible heat transfer/latent heat transfer)}$$

$$\Delta \text{T}_{\text{sup}} = T_\infty - T_{\text{sat}}\left(p_\infty\right) : \text{superheat}$$

Details of MRG Model (1970)

$$R^+ = \frac{2}{3}\left[\left(t^+ + 1\right)^{3/2} - \left(t^+\right)^{3/2} - 1\right]$$

where

$$R^+ = \frac{A}{B^2}R, \quad t^+ = \left(\frac{A}{B}\right)^2 t$$

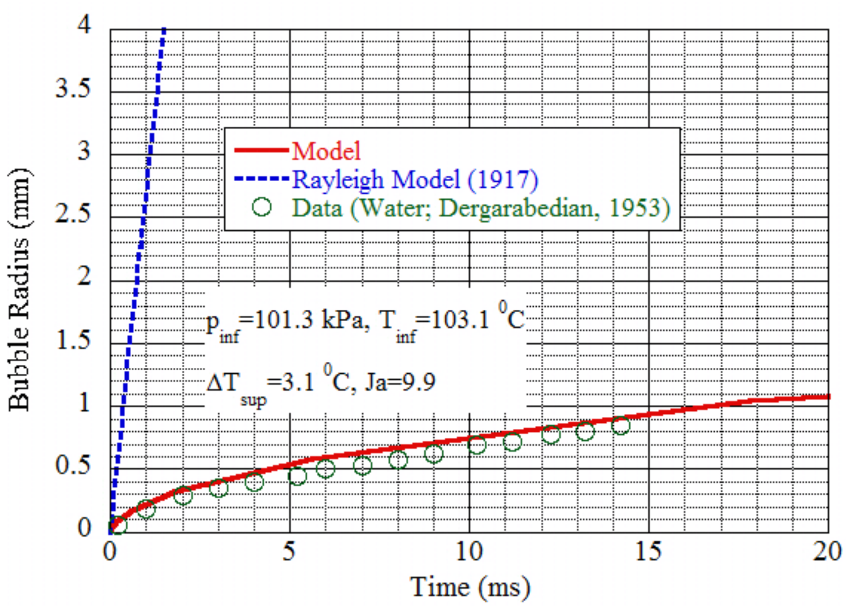
$$A = \left[\frac{2}{3}\frac{h_{fg}\rho_v \Delta T_{\text{sup}}}{\rho_f T_{\text{sat}}}\right]^{1/2}, \quad B = \left(\frac{12}{\pi}\alpha_f\right)^{1/2}\left[\frac{\Delta T_{\text{sup}}}{\left(\rho_v\right)_{T_{\text{sat}}}}\right]\frac{c_f \rho_f \Delta T_{\text{sup}}}{h_{fg}\rho_v}$$

Limiting Cases

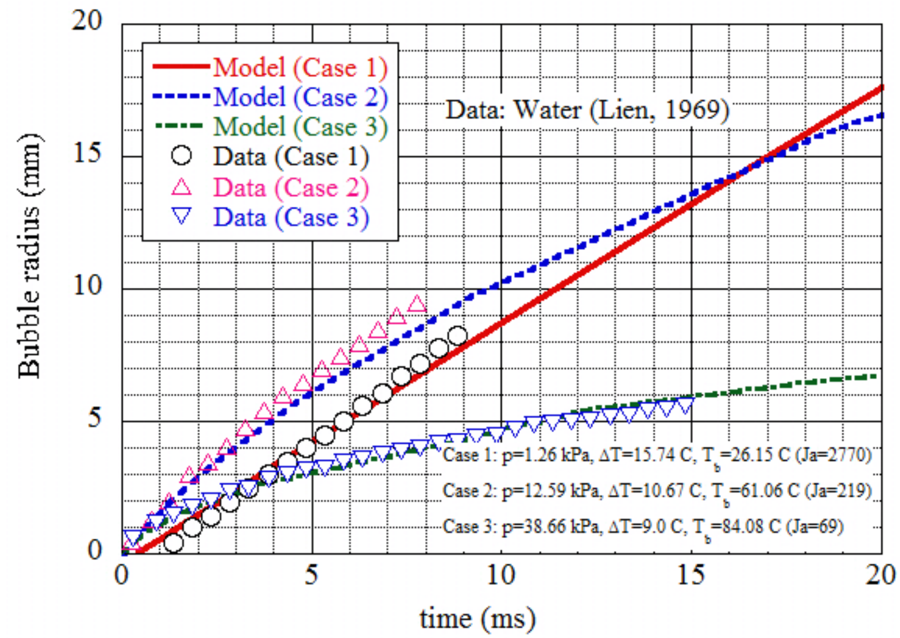
$R^+ = t^+$ or $R = At$: Rayleigh solution (inertia - controlled, small time)

$\mathrm{R}^+ = \sqrt{t^+}$ or $R = B\sqrt{t}$: Plesset & Zwick solution (diffusion - controlled, large time)

Validation with Bubble Growth Data (Unbounded Medium)



Data of Dergarabedian (Caltech,1953)



Data of Lien (MIT,1953)

- *Satisfactory agreement is achieved between the model predictions and the test data for water covering a wide range of system pressures and superheats.*
- *The data include both inertia-controlled and heat-diffusion-controlled regions.*

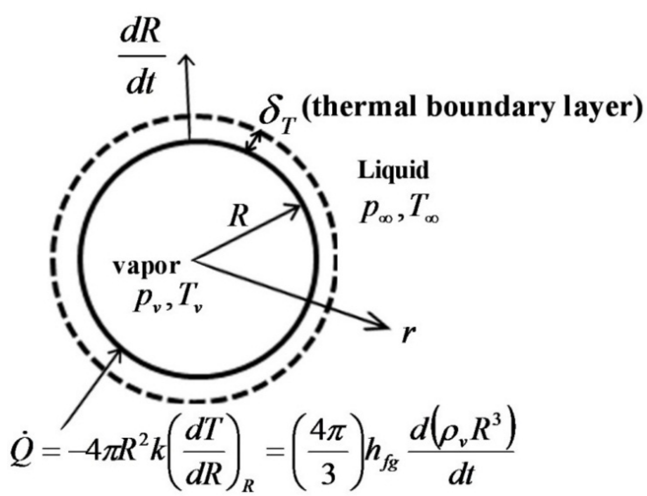
Vented Liquid Jets in Vacuum

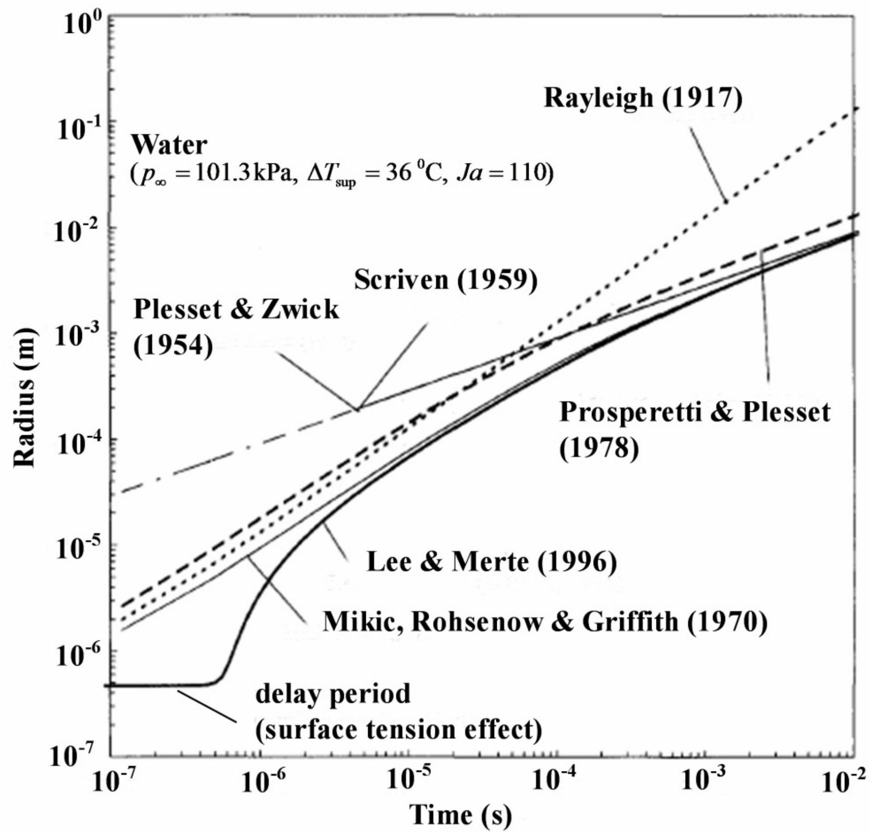
- Fuchs & Legge (1970)
  - Provides a qualitative picture of jet bursting and dispersion
  - Presents photographic evidence on jet burst lengths
  - Investigates analytically jet surface cooling
  - Offers no theoretical model for jet disintegration

- Muntz & Orme (1987)
  - Assumes bubble burst *when bubble size equals the jet diameter*
  - Neglects surface tension effects and initial bubble radius
  - Underpredicts jet bursting length by an order of magnitude

Comparisons of Bubble Growth Models for an Unbounded Medium

(Uniformly Superheated Liquid)

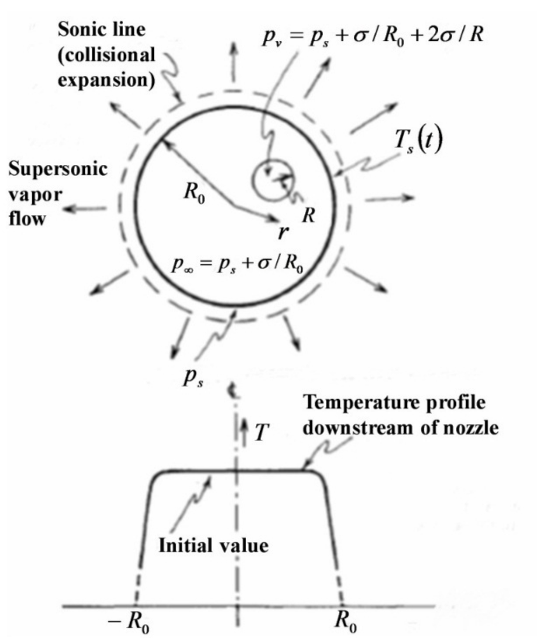




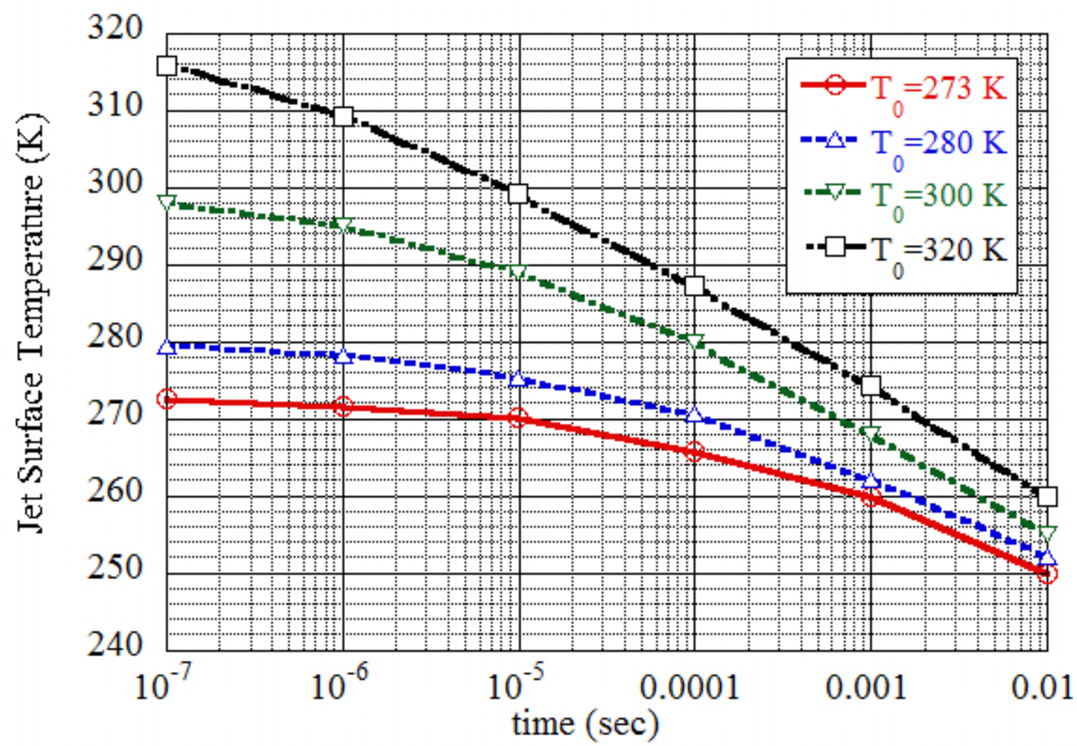
- *For small times, the system is isothermal and bubble grows by pressure expansion.*
- *For large times, the pressures tend to equalize, and bubble growth by vaporization is controlled by the rate of heat diffusion from the liquid to the bubble.*

Flashing Liquid Jets
Jet Surface Temperature

Ref: Fuchs & Legge (1970), Muntz & Orme (1987)

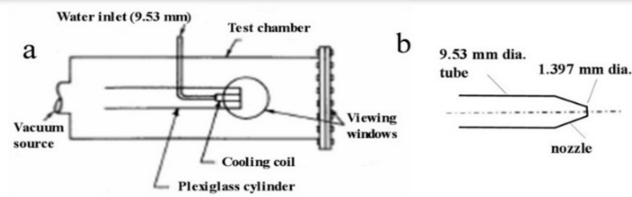


Bubble growth inside jets

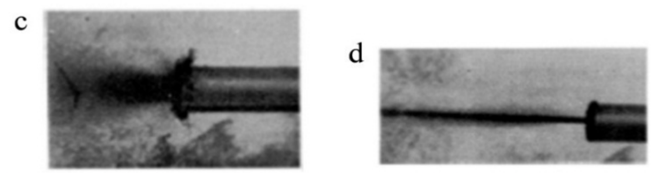


- *The jet surface rapidly cools upon depressurization due to surface evaporation.*
- *This surface temperature governs the local pressure within the liquid.*

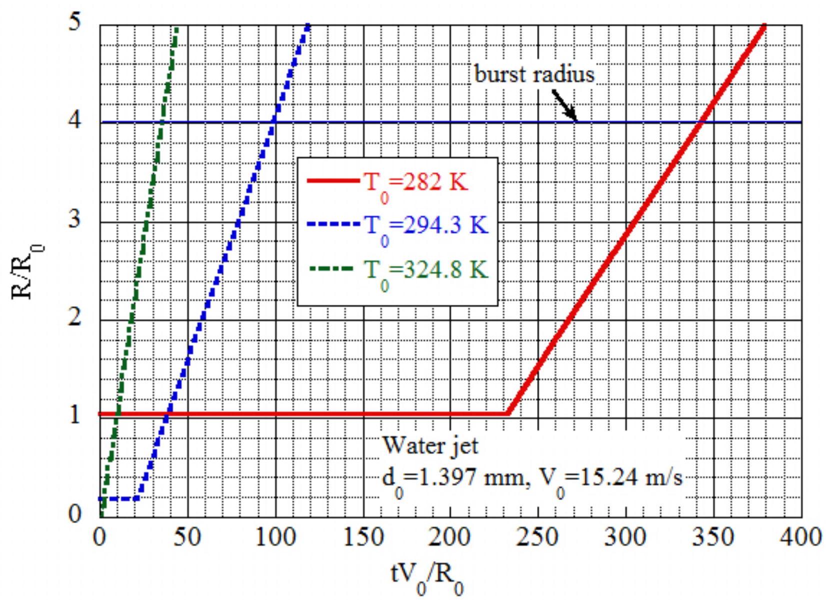
Comparison for Flashing Jets
Data of Mann & Stoll (1964)



Nozzle configuration



Jet structure



Predicted
Bubble growth

- The predicted bubble growth is seen to be linear as in the previous test data.

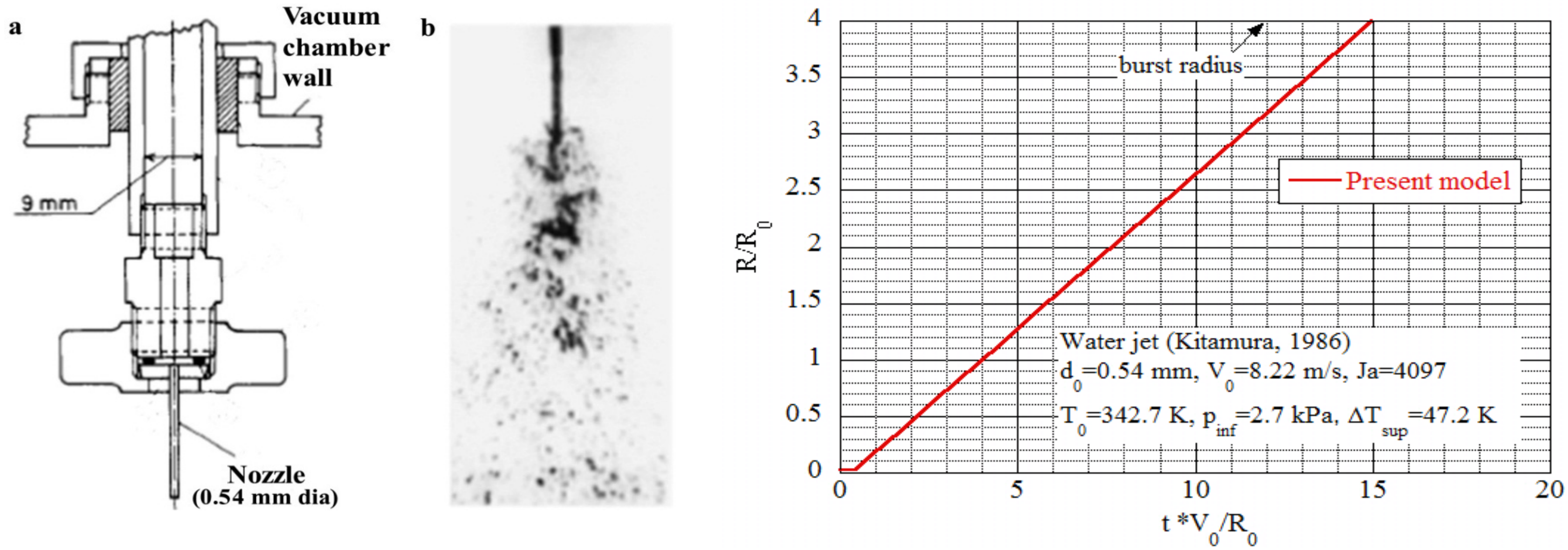
Comparison for Flashing Jets
Data of Mann & Stoll (1964): contd.

Quantity	T_0=324.8 K		T_0=294.3 K		T_0=282 K	
	Model	Data	Model	Data	Model	Data
Bursting distance (jet diameters)	17.3	23	49.1	38	173.3	-*
Included cone angle (deg)	13.6	30	5.7	4	2.3	-

*No bursting is observed within the available chamber length.

- Reasonable comparison is achieved at jet temperatures of 325 K and 295 K.
- At 282 K, the jet does not break up within the chamber length.

Comparison for Flashing Jets
Data of Kitamura et al. (1986)

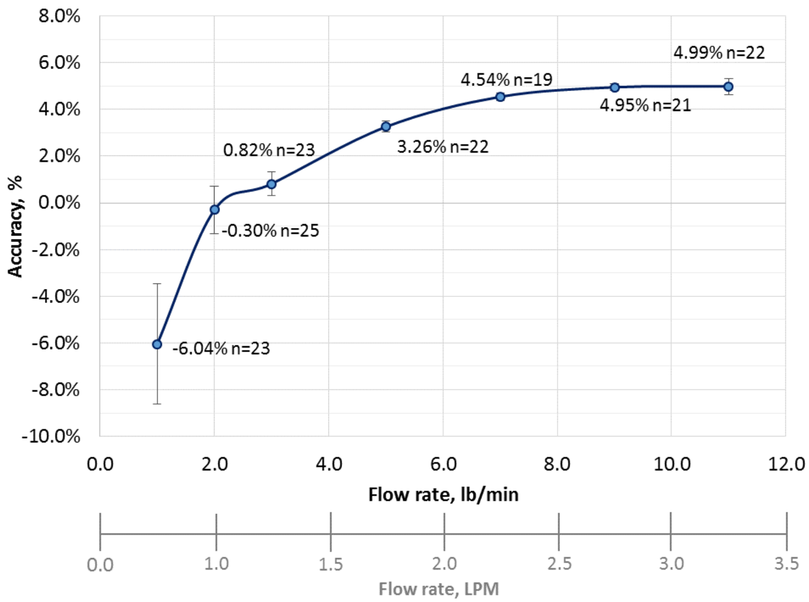


Quantity	Model	Data
Bursting distance (jet diameters)	7.5	13
Included cone angle (deg)	28.6	38

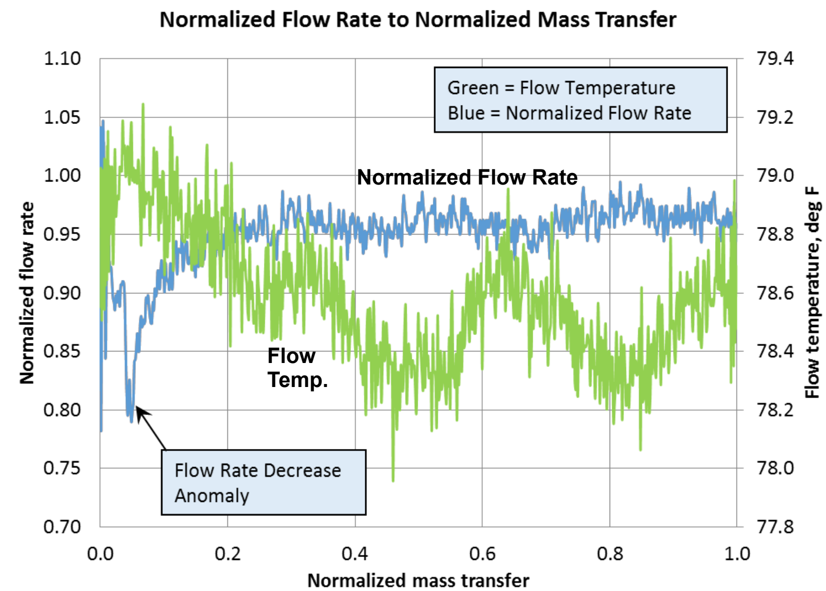
- Tolerable comparison is achieved at jet temperatures of 343 K.
- The model underpredicts the burst distance and the cone angle of dispersion.

Flow Meter Testing
Back-Up Slides

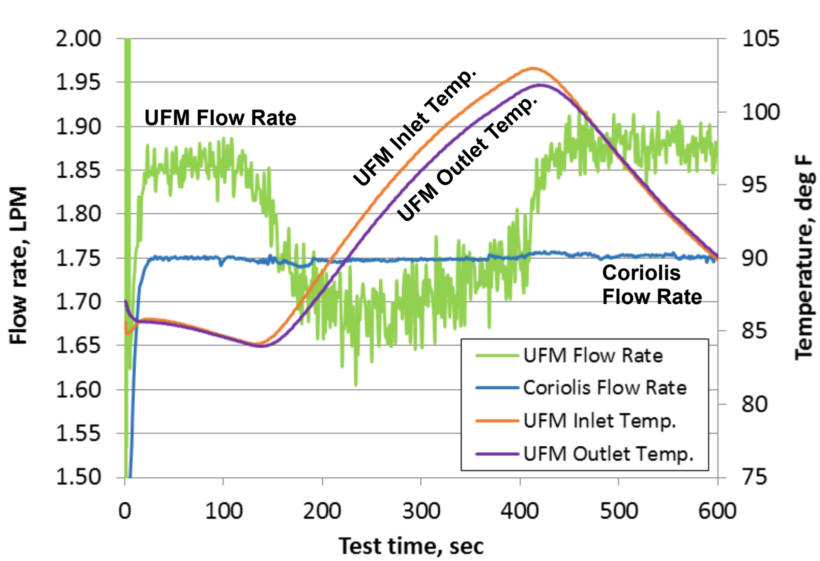
UFM Graphs



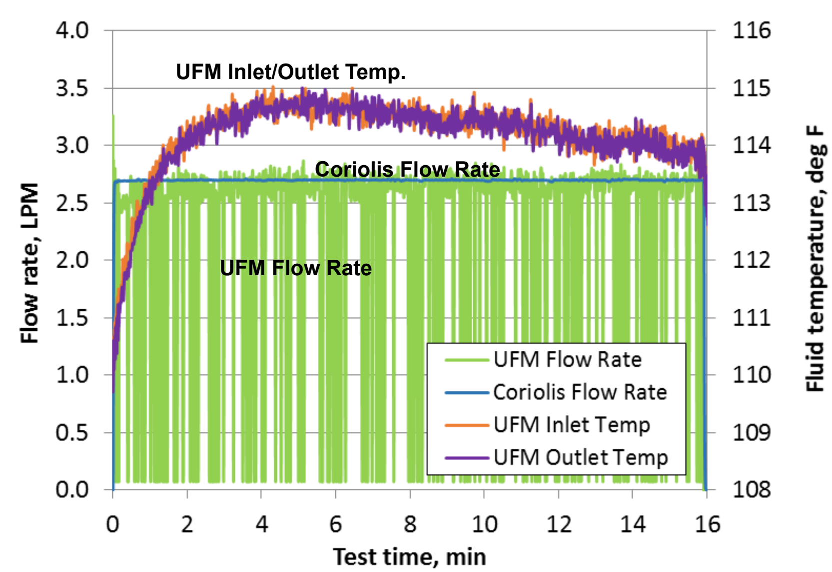
8.0%
6.0%
4.0%
2.0%
0.0%
-2.0%
-4.0%
-6.0%
-8.0%
-10.0%
Accuracy, %
4.99% n=22
4.54% n=19
4.95% n=21
0.82% n=23
3.26% n=22
-0.30% n=25
-6.04% n=23
0.0 2.0 4.0 6.0 8.0 10.0 12.0
Flow rate, lb/min
0.0 1.0 1.5 2.0 2.5 3.0 3.5
Flow rate, LPM



Normalized Flow Rate to Normalized Mass Transfer
Green = Flow Temperature
Blue = Normalized Flow Rate
Normalized Flow Rate
Flow Temp.
Flow Rate Decrease Anomaly
Normalized flow rate
1.10 1.05 1.00 0.95 0.90 0.85 0.80 0.75 0.70
79.4 79.2 79.0 78.8 78.6 78.4 78.2 78.0 77.8
Flow temperature, deg F
0.0 0.2 0.4 0.6 0.8 1.0
Normalized mass transfer

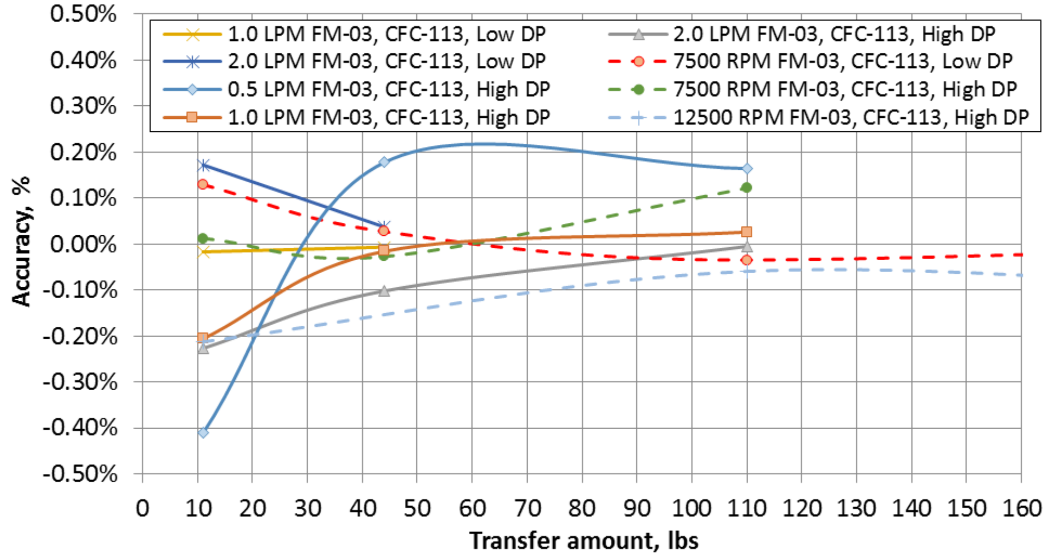


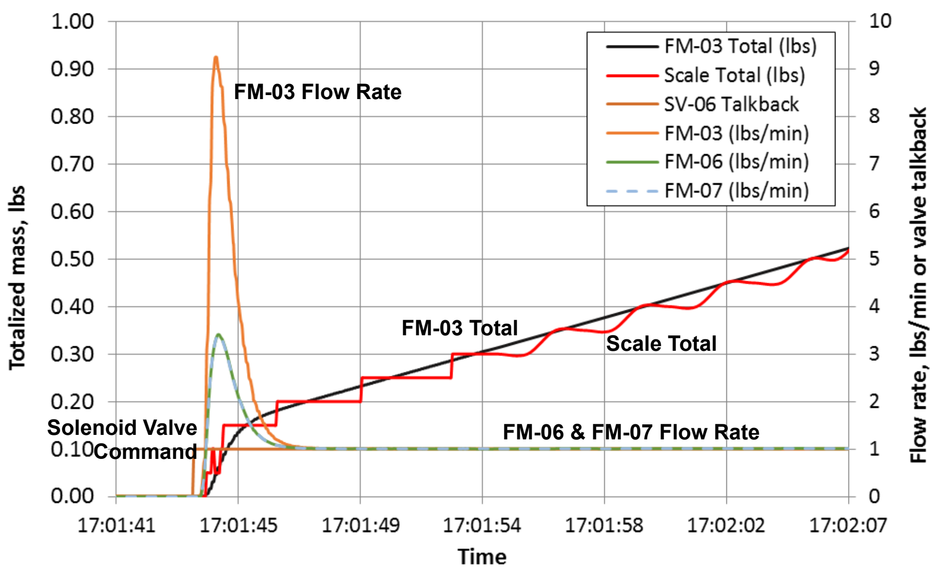
UFM Flow Rate
UFM Inlet Temp.
UFM Outlet Temp.
Coriolis Flow Rate
UFM Flow Rate
Coriolis Flow Rate
UFM Inlet Temp.
UFM Outlet Temp.
Flow rate, LPM
2.00 1.95 1.90 1.85 1.80 1.75 1.70 1.65 1.60 1.55 1.50
105 100 95 90 85 80 75
Temperature, deg F
0 100 200 300 400 500 600
Test time, sec

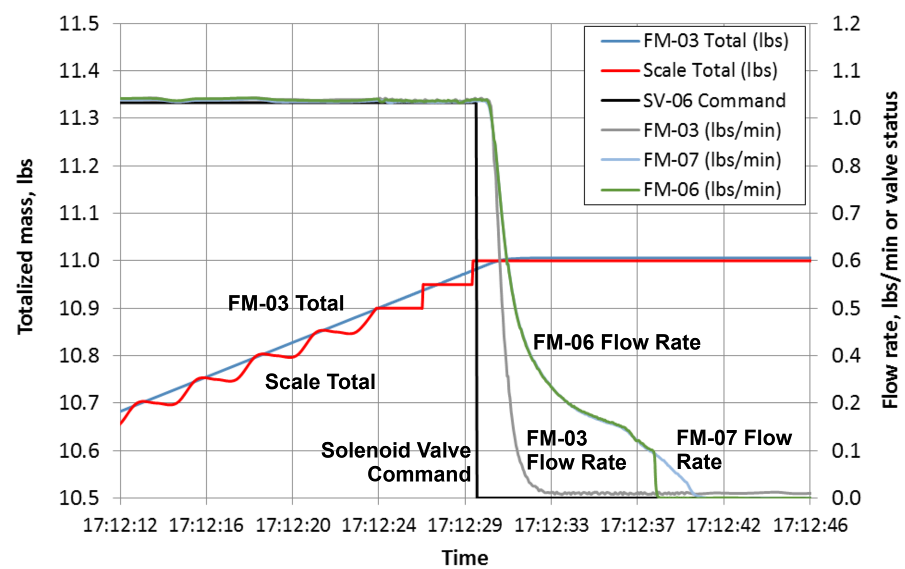


UFM Inlet/Outlet Temp.
Coriolis Flow Rate
UFM Flow Rate
UFM Flow Rate
Coriolis Flow Rate
UFM Inlet Temp
UFM Outlet Temp
Flow rate, LPM
4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
116 115 114 113 112 111 110 109 108
Fluid temperature, deg F
0 2 4 6 8 10 12 14 16
Test time, min

Coriolis Graphs







Historical Flow Meter Testing for On Orbit Fueling By Baird

- Baird presented results for static ground, vibration ground, and zero-g testing (limited duration parabolic flight tests)
- Flow metering concepts, capabilities, limitations, and testing for on-orbit fluid transfer operations were discussed.
- Basic operating principles of each of the flow meters evaluated were summarized, and selection criteria for the best flow meter(s) for each application were reported based on the limited data set that was available
- Flow meter concepts tested included
  - Clamp-on ultrasonic, area averaging ultrasonic, offset ultrasonic, Coriolis mass, vortex shedding, universal venturi tube, turbine, bearing-less turbine, turbine/ turbine differential pressure hybrid, drag-body, and drag-body/turbine hybrid flow meters
- Flow meter selection considerations discussed
  - Performance, fluid operating conditions, system operating environments, packaging, maintenance, and overall technology